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# EVALUATION OF THE EFFECTS OF THERAPEUTIC ULTRASOUND FREQUENCIES ON NERVE CONDUCTION VELOCITY

by

GORDON ALEXANDER RENNIE

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

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OF MASTER OF SCIENCE

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## DEDICATION

To the memory of my brother Bob, for his unending faith, support and love.

**ABSTRACT**

The purpose of this study was to examine the effects of different frequencies of therapeutic ultrasound on motor and sensory nerve conduction velocity. Nineteen female subjects aged 19 to 24 years (mean age 20.4 years) were tested on four occasions, with a different ultrasound frequency used for each test. The frequencies used were 0.75, 1.5, 3.0 and 0.0 (control) MegaHertz, and were assigned randomly to each subject. The intensity (1.5 Watts per centimeter squared continuous mode) and duration (five minutes) of ultrasound application were constant for each subject. The ultrasound was applied to a ten to thirteen centimeter segment of the ulnar nerve coursing proximally from the ulnar groove on the postero-medial aspect of the elbow. Motor and sensory nerve conduction data were collected four times during the test procedure: 1) one minute pre-treatment, 2) immediately pre-treatment, 3) immediately post-treatment, and 4) one minute post-treatment.

A two way analysis of variance with repeated measures over four levels of both factors was used to analyze the data. The results indicated there were significant differences in pre and post-treatment motor and sensory nerve conduction velocities for all ultrasound frequencies. Tukey post hoc tests demonstrated a significant difference between one pair of frequencies (0.0 MHz versus 3.0 MHz) for both motor and sensory conduction velocities. No other pairs of ultrasound frequency produced significant changes in

nerve conduction velocities.

The results suggest two possible causes for the significant differences: a) the cooling effect of the ultrasound transmission gel caused the decrease in motor and sensory conduction velocities with 0.0 MHz ultrasound, and b) the large increases in motor and sensory conduction velocities with 3.0 MHz ultrasound occurred due to more superficial absorption of the ultrasound energy. The superficial (subcutaneous) location of the ulnar nerve appeared to demonstrate a greater affinity for absorption of high frequency ultrasound than low frequency ultrasound.

The present study has provided information suggesting different frequencies of therapeutic ultrasound energy are absorbed at different depths in human tissue.

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# Chapter I

# THE PROBLEM

## A. Introduction

Therapeutic ultrasound has been reported to increase sensory nerve conduction velocity (SNCV),[1-4] and to both increase[5,6,8-10] and decrease[5-8] motor nerve conduction velocity (MNCV). The increases occurring in nerve conduction velocity are reported to be due to the thermal (heating) effects of ultrasound.[1-4,8-10]

Therapeutic ultrasound can be delivered via a continuous or pulsed mode,[11-14] and at different frequencies.[11-23] It has been indicated that continuous ultrasound produces thermal and non-thermal effects, while pulsed ultrasound produces mainly non-thermal (mechanical) effects.[2-5,9,10] The frequency at which ultrasound can be delivered is variable within a range of 0.75 MegaHertz (MHz) to 3.0 MHz, and the majority of ultrasound machines are manufactured to deliver a fixed frequency somewhere within that range. More recently, ultrasound machines are being manufactured that allow for two or more frequencies to be selected.[21-23]

Different frequencies of ultrasound are reported to produce physiological effects at various depths in human tissue.[11-22] This occurs due to the fact that the wavelength of ultrasound is frequency dependent: the higher the frequency, the shorter the wavelength; the lower the

frequency, the longer the wavelength. A high frequency, short wavelength ultrasound beam will travel less far in human tissue than a low frequency, long wavelength ultrasound beam.[11-22]

As ultrasound penetrates human tissue, it is exponentially attenuated, with the major component of attenuation being absorption[11-20] (Figure 1). The term used to describe the depth at which ultrasound intensity is attenuated by fifty per cent of its original intensity is half-value thickness or half-value depth.[11-16,18,20] The half-value thickness in humans changes relative to ultrasound frequency and nature of the biological tissue exposed to ultrasound.[11-16,18,20] The literature reports differences in depths of penetration in human tissue (Table 1), although many of the values obtained are not substantiated by scientific evidence. Clinically, it is suggested that high frequency ultrasound (3.0 MHz) is used for superficial treatments, and low frequency ultrasound ($\leq$ 1.0 MHz) is used for deeper treatments.[11-22] In the majority of physiotherapy departments and clinics however, ultrasound units have one fixed frequency.[23] Thus all treatments, whether superficial or deep, are with an ultrasound unit with a frequency that cannot be changed.

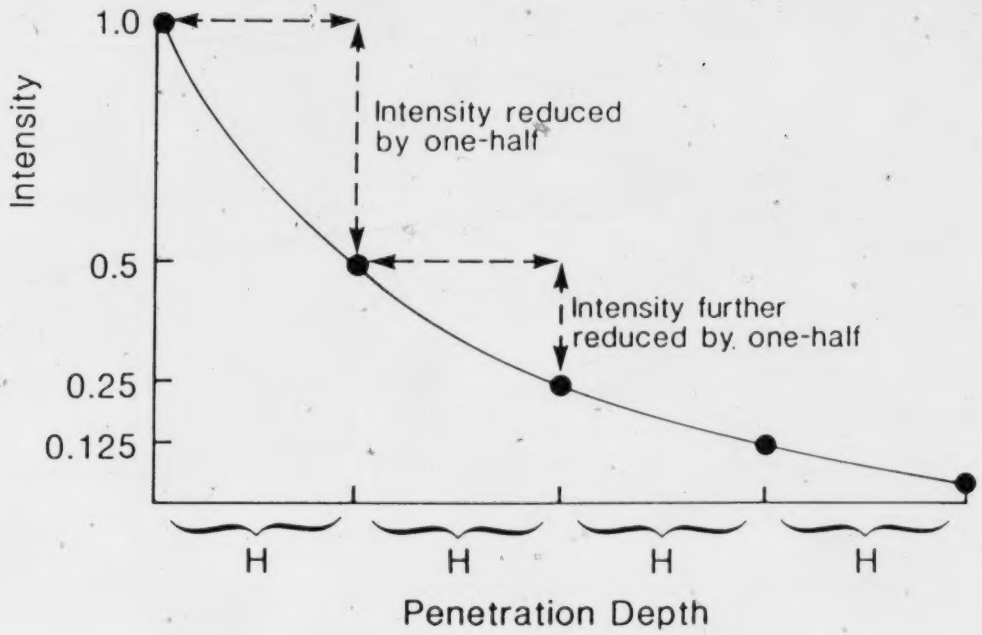



FIGURE 1: Exponential attenuation of ultrasound intensity. The intensity is halved each time a depth of "one half-value thickness (H)" is reached.
Reid, D.C.: Therapeutic Ultrasound. Master of Orthopaedic Surgery Thesis, University of Liverpool, 1980

TABLE 1

Summary of reported half-valve thickness penetration of ultrasound of different frequencies into human tissue

| Ultrasound Frequency (MHz) | Human Tissue half-value thickness in centimeters | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Fat | | Muscle | | Bone | | Not specified | |
| 0.75 | | | 3.0 | (Nightingale, 1959) | | | 9.0 | (Wadsworth and Chanmugam, 1983) |
| 1.0 | 4.95 | (Stewart et al, 1982) | 2.30 | (Stewart et al, 1982) | 0.040 | (Reid, 1980) (Ward, 1980) | 4.0 | (ter Haar, 1978) |
| | 15.28 | (Reid, 1980) (Ward, 1980) | 2.78 | (Reid, 1980) (Ward, 1980) | 0.23 | (Stewart et al, 1982) | 5.0 | (Farris, 1969) |
| | | | | | | | 5.0 | (Summer and Patrick, 1964) |
| | | | | | | | 6.5 | (Wadsworth and Chanmugam, 1983) |
| 1.5 | | | 1.0 | (Nightingale, 1959) | | | 5.5 | (Wadsworth and Chanmugam, 1983) |
| 2.0 | 5.14 | (Reid, 1980) (Ward, 1980) | 1.25 | (Reid, 1980) (Ward, 1980) | 0.010 | (Reid, 1980) (Ward, 1980) | | |
| 3.0 | 2.64 | (Reid, 1980) (Ward, 1980) | 0.76 | (Reid, 1980) (Ward, 1980) | 0.004 | (Reid, 1980) (Ward, 1980) | 1.5 | (Summer and Patrick, 1964) |
| | | | 1.0 | (Nightingale, 1959) | | | 2.5 | (ter Haar, 1978) |
| | | | | | | | 2.5 | (Wadsworth and Chanmugam, 1983) |

**B. Statement of the Problem**

The majority of the therapeutic effects of ultrasound are reported to be thermal when using a continuous mode of delivery. Furthermore, it is conceivable that more heating will occur in superficial tissues using high frequency ultrasound as opposed to low frequency ultrasound. However, there is nothing in the literature that compares different ultrasound frequencies delivered by the same machine with respect to the thermal effects generated at various tissue depths. The problem, therefore, is to determine if varying frequencies of ultrasound produce significant differences in thermal (heating) effects in subcutaneous human tissue as evidenced by changes in NCV when exposed to ultrasound. Absorption of ultrasound by peripheral nerves has been reported as being quite high, due to the high amount (10-15%) of protein contained in peripheral nerves.[20,25] Fatty tissue, on the other hand, is a poor absorber of ultrasound.[20,25] The relationship between absorption and transmission is depicted in Table 2. The anatomical location of superficial (subcutaneous) peripheral nerves would therefore allow for ultrasound transmission through the skin, fascia and subcutaneous fatty layer and preferential absorption by the nerve. The effects of ultrasound on NCV have been demonstrated as being primarily thermal, resulting in an increase in NCV.[1-4,8-10] If the nerve exposed to ultrasound is superficially (subcutaneously) located, different ultrasound frequencies should demonstrate

different changes in NCV due to the differential in depth of penetration of ultrasound.

Specifically, the higher frequencies should produce more heating in the superficial structures, and this in turn, should be reflected in increased conduction velocities of superficially located nerves.

TABLE 2

Relationship between absorption and penetration
(Ultrasound frequency = 1 MegaHertz)

| Media | Absorption | Penetration |
|---|---|---|
| Water | 1 | 1200 |
| Blood Plasma | 23 | 52 |
| Whole Blood | 60 | 20 |
| Fat | 390 | 4 |
| Skeletal Muscle | 633 | 2 |
| Peripheral Nerve | 1193 | 1 |

Table compiled by Griffin (25). Arbitrary units.
Tissues of high water content have little absorption and tissues of high protein content exhibit the most absorption.
Penetration is inversely proportional to absorption.[20]

## C. Objective of the Study

The primary objective of this study was to insonate a segment of the ulnar nerve with different frequencies of therapeutic ultrasound and to record motor and sensory nerve conduction velocities pre and post-ultrasound treatment.

## D. Research Hypotheses

(i) There will be significant differences in the post-treatment motor nerve conduction velocities associated with four different ultrasound frequencies.

(ii) There will be significant differences in the post-treatment sensory nerve conduction velocities associated with four different ultrasound frequencies.

(iii) The magnitude of the post-treatment change in motor and sensory nerve conduction velocities will be related to the frequency of ultrasound.

## E. Operational Definitions

### Therapeutic Ultrasound

Ultrasound is defined as mechanical vibration with acoustic frequencies above those of audible sound.[1-4] The range of audible sound of human hearing is 20 to 20,000 Hertz; therapeutic ultrasound frequency ranges from 0.75 to 3.0 MHz.[1-4] Therapeutic ultrasound is used to provide a

variety of therapeutic benefits to patients, based on its thermal and non-thermal effects.

**Continuous/Pulsed Ultrasound**

Continuous ultrasound is delivered uninterrupted over time, at a specific frequency and intensity. Continuous ultrasound, through molecular vibration, produces a heating or thermal effect in human tissues.[2-8,9-16,18-20] Pulsed ultrasound is delivered interrupted over time, according to a duty cycle or pulse ratio.[11-16,18,20] A pulse ratio or duty cycle of 1:4 indicates the ultrasound is "on" for only one-fifth of the total insonation time. Pulsed ultrasound does not produce a significant heating effect due to the length of the "off" time, during which any thermal energy build-up is dissipated or minimized.[11-16,18,20]

**Intensity**

Therapeutic ultrasound is delivered at an intensity measured in watts per centimeter squared ($W/cm^2$), which is determined by dividing total power output (Watts) by the effective (cross-sectional) area of the ultrasound transducer head ($cm^2$).[11-16,18,20] Therapeutic ultrasound intensities range between 0.1 $W/cm^2$ and 3.0 $W/cm^2$.[11,12,14-16,20]

**Therapeutic Ultrasound Dosage**

Therapeutic ultrasound dosage is chosen arbitrarily, and the literature reports no specific dosages have been conclusively proven to be related to specific physiological responses. Dosage refers to the intensity ($W/cm,^{2}$) and the time in minutes of ultrasound delivered. Wadsworth and Chanmugam[11] have recently produced a guideline for therapeutic ultrasound dosage, and they (along with several others[12,14-16,24]) recommend continuous ultrasound for 5 minutes at an intensity between 1.0 and 2.0 $W/cm^{2}$ for the thermal effects. Reid[20] suggests an intensity range of 1.5 to 3.0 $W/cm^{2}$ for thermal effects.

**Motor Nerve Conduction Velocity (MNCV)**

Motor nerve conduction velocity is the difference in latencies (stimulation and response) divided by the distance between the two points of stimulation, and is measured in meters per second (m/s).[27] The normal motor NCV for the ulnar nerve is in the range of 47-73 m/s with a mean of 59.4 m/s.[27]

**Sensory Nerve Conduction Velocity (SNCV)**

Sensory nerve conduction velocity is the difference in latencies (stimulation and response) divided by the distance between the two points of stimulation, and is measured in meters per second (m/s).[27] Normal sensory nerve conduction velocities are 3-6 m/s faster than motor conduction

velocities.[27]

**F. Limitations of the Study**

1. The ability to consistently stimulate for NCV's accurately over the same nerve points on successive occasions will be limited by the accuracy and technique of the investigator.
2. The accuracy of recording and analyzing the NCV's (motor and sensory action potentials) from one occasion to the next will be limited to the accuracy and technique of the investigator.
3. The accuracy and consistency of ultrasound applications on successive applications is limited to the technique used by the investigator.

**G. Delimitations of the Study**

1. The study will be limited to 16 to 20 female volunteers between the ages of 18 and 25, who are informed volunteers with no known pathology or disease.
2. The study will be limited to the intensity, duration and frequencies of therapeutic ultrasound as selected by the investigator.
3. The study will be limited to the parallel stroking method of ultrasound application, given over the medial aspect of the distal segment of

the dominant arm.

4. The study will be limited to testing of each subject with a minimum of 24 hours rest between tests to ensure no effects from the previous test have carried over.

## Chapter II

## REVIEW OF THE LITERATURE

### A. Introduction

Therapeutic ultrasound is an electrophysical agent with its effects occurring in human tissue due to thermal and mechanical phenomena. Pohlman, in 1939, (cited in Reid[20]) was the first person to demonstrate the therapeutic effects of ultrasound when he advocated its use for sciatica. Since that time, therapeutic ultrasound has become a very widely used electrophysical agent in medicine. Although it has been used therapeutically for nearly fifty years, it is still one of the most controversial electrophysical agents used by physiotherapists and medical practitioners.[20] This is due partly to the difficulty in understanding the underlying physics associated with sound transmission, and partly due to relatively few well controlled clinical and laboratory investigations into its effects and uses.[20] One method of determining the selective heating of human tissue exposed to therapeutic ultrasound is to measure and record its effects on nerve conduction velocity.[1-10] The amount of selective heating is reported to be partially dependent upon the frequency of the ultrasound.[11-20] Measurement of changes in nerve conduction velocity as a result of exposure to different ultrasound frequencies is one method of indirectly determining the thermal effects of therapeutic ultrasound. To this investigator's knowledge, this method has not been

reported in the literature.

**B. Ultrasound and Heating of Tissue**

At any given temperature above absolute zero, the molecules within a tissue are in a constant state of motion or agitation.[15,20] This molecular motion occurs at an average frequency, and this frequency of molecular motion is how the heat of the body is measured.[15] Ultrasound waves produce mechanical vibrations at a specific frequency and in a longitudinal direction.[13-15,20,29] As the ultrasound moves through the tissues, it causes the molecules to oscillate in the direction of ultrasound propagation, while the molecules are naturally oscillating in all directions. These directions are continually and randomly changing as a result of collisions.[15,20] The tendency is for the collisions to randomize in the direction of the ultrasound vibrations and so convert sound energy into heat energy.[15,20] If any natural oscillation of the molecule corresponds to the frequency of the ultrasound wave, then the sound will be progressively absorbed in the medium, thus being converted into heat energy.[15] When the ultrasound frequency differs from the average natural frequency of molecular movement, the natural range of frequency of the molecules will enable some energy to be absorbed, and therefore some heat will be produced.[15]

The amount of ultrasound absorption is primarily dependent upon two factors: (i) the frequency of the

ultrasound wave; and (ii) the nature of the medium to which it is applied.

**C. Frequency of Ultrasound and its Effects on Human Tissue**

The higher the frequency of ultrasound, the shorter the wavelength, the more superficial the absorption and the less the penetration depth. Conversely, the lower the frequency, the longer the wavelength, the deeper the absorption and the greater the penetration depth.[11-14,20] There has been comprehensive data gathered on the depth of penetration and absorption of ultrasound at various frequencies,[30,31] but very little information is available comparing the effects of different ultrasound frequencies on human tissue.

Griffin et al[17] compared the effects of 0.89 MHz and 1.0 MHz ultrasound frequencies in one hundred and twenty patients diagnosed as having chronic osteoarthritis or periarticular dysfunction involving the shoulder, thoracic or lumbar vertebrae, hip or knee. Sixty patients received 0.89 MHz ultrasound, and sixty patients received 1.0 MHz ultrasound; standard treatment time was five minutes per twenty-five square inches of area. Intensity did not exceed 1.5 $W/cm^2$ for shoulder or knee treatments, and did not exceed 2.0 $W/cm^2$ when ultrasound was applied paravertebrally or to the hip area. All patients were treated three times a week for a total of nine treatments (unless pain relief was achieved earlier), and at each hospital all treatments were administered by the same therapist. The ultrasound units and

transmission gel used were the same at all hospitals.

Patients were evaluated by their referring physician after completion of the treatment as being improved, partially improved or unimproved. The rating scale was based on relief of pain on active movement and presence of a functional range of motion. Griffin found 63.5% of the patients treated with 0.89 MHz were evaluated as improved, compared to 30.3% of the patients treated with 1.0 MHz. He then combined the improved and partially improved patient groups, and stated that 92% of those treated with 0.89 MHz compared to 69% of those treated with 1.0 MHz, responded favorably. Griffin stated the significant differences observed in patient responses to treatment were brought about by the effectiveness of treatment with 0.89 MHz ultrasound in the management of pain with chronic osteoarthritis, due to a greater depth of penetration of ultrasound at that frequency. He suggested that when patients with similar lesions do not respond satisfactorily with 1.0 MHz ultrasound, treatment with a lower frequency be considered.

Although the results of Griffin's study might be considered encouraging from a clinical standpoint, it is difficult to assess how effective the ultrasound treatments were, based on the methodology of the study. The diagnoses of chronic osteoarthritis and periarticular dysfunction gave no indication of length of illness, severity, swelling, inflammation or other forms of treatment (i.e. medications),

all of which could affect the effectiveness of ultrasound treatment. The ultrasound intensities were not consistent throughout the study, ranging from an unknown minimum to a maximum of 1.5 and 2.0 W/cm². As there was no control group of patients, it is difficult to determine how significant the improvements in pain and functional range of motion were with the ultrasound treatment compared to another form of treatment or no treatment.

Fyfe[21] studied the effects of different ultrasound frequencies on experimental oedema. Her hypothesis was that 3 MHz ultrasound may be most effective in the treatment of superficial lesions, whereas a lower frequency may be better for deeper-seated lesions. Experimental oedema was induced in an unknown number of rats by injecting 0.05ml of silver nitrate intra-cutaneously on each side of the abdomen mid-way between the ribcage and the pubis. An albumin-binding dye, Evans blue, in a dose of 2.5ml/kg of a 2 per cent solution was injected into a tail vein. Immediately after the silver nitrate injections, one of the sites was insonated and the other site mock-insonated with an identical technique but with zero ultrasound intensity. The treatments were grouped according to ultrasound frequency (0.75 MHz, 1.5 MHz and 3.0 MHz) and pulse-ratio (1:1 and 1:4), and all treatments were given with an ultrasound intensity of 0.5 W/cm² pulsed mode. Treatment durations for each of the three frequencies and pulse-ratios were 2, 3, 4 and 5 minutes for successive groups of animals.

Following the ultrasound treatments, the rats were killed, and the areas of skin treated were placed in reagent bottles containing 3ml of 0.5 per cent sodium sulphate and 7ml of acetone. The dye was extracted by the reagents and the amount of dye was measured spectrophotometrically and expressed as absorbances. Quantitative comparison of the oedema at insonated and mock-insonated sites was then measured. The results demonstrated no significant differences between the insonated and mock-insonated groups treated with 3.0 MHz and 1.5 MHz ultrasound. With a frequency of 0.75 MHz, there were significant reductions in oedema with 2 and 4 minute treatments and at both pulse-ratios. Fyfe stated these results were unexpected, and suggested further work would be necessary to determine the relative importance of variations in duration, frequency and intensity of ultrasound to its effectiveness. The results of this study demonstrated that ultrasound was capable of limiting the development of oedema, although they do not indicate anything about the effect of ultrasound on oedema resolution.

Clarke and Stenner[23] conducted a clinical trial comparing the effects of different ultrasound frequencies on patients with rheumatoid nodules, and another group of patients with plantar fasciitis. The trial of patients with rheumatoid nodules proved inconclusive, primarily due to the fact that four of the eight patients were classified as having severe sero-positive and erosive nodules. There was

no consistent trend of improvement in either the control or treated groups of patients.

A group of nine patients diagnosed as having plantar fasciitis were treated with different frequencies (0.75 MHz, 1.0 MHz, 1.5 MHz and 3.0 MHz), different intensities (range 1.0 to 2.5 $W/cm^2$), and two of the nine patients were treated with pulsed ultrasound (no pulse-ratio given). Treatment times for continuous ultrasound ranged from five to ten minutes per treatment; pulsed ultrasound treatment times ranged from three to ten minutes. The number of treatments per patient ranged from three to thirteen.

Although the authors state their results demonstrated a subjective improvement in eight of nine patients, no statistical analysis was done to attempt to show significant changes. The patients were not grouped according to frequency, and two of the patients were treated with two different frequencies. From their results it is difficult to determine if any one ultrasound frequency demonstrated any greater or lesser effect in the treatment of plantar fasciitis.

**D. Ultrasound and Nerve Conduction Velocity**

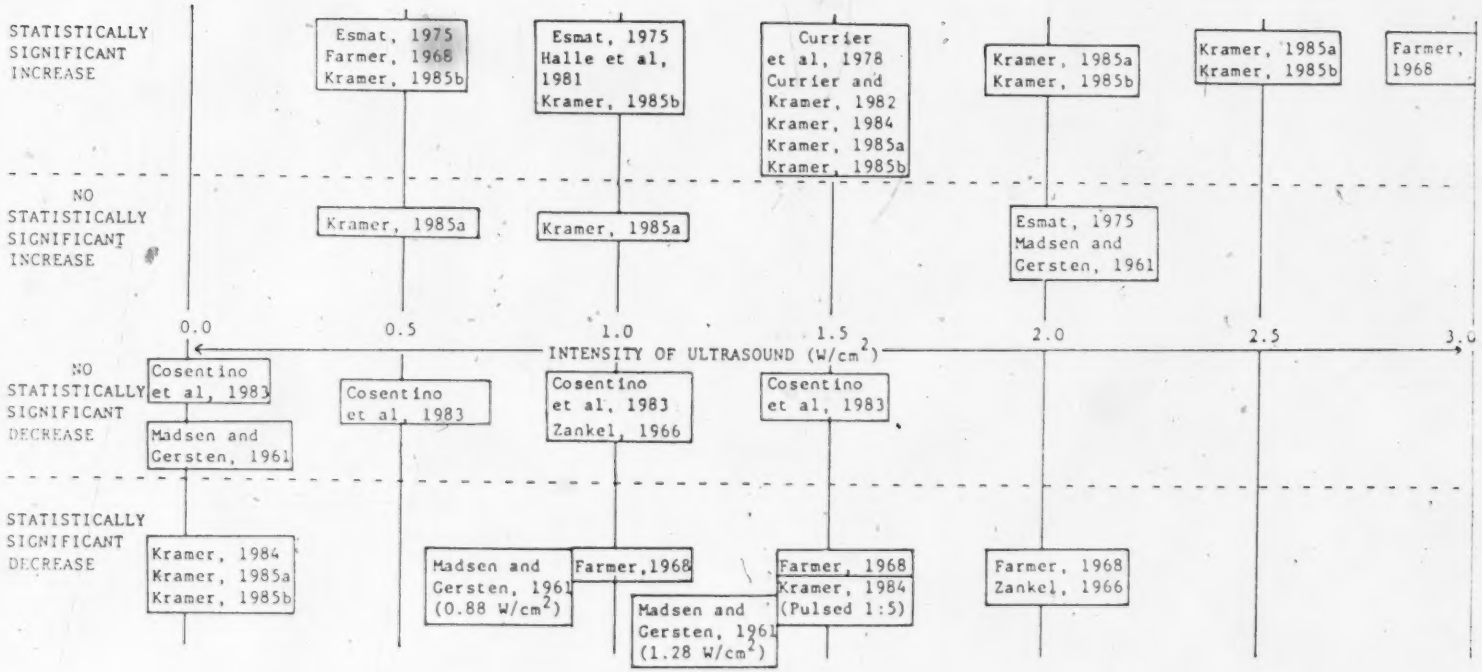
Studies indicate that peripheral nerves absorb ultrasound quite readily,[20,25] and that the anatomical location of superficial (subcutaneous) peripheral nerves would demonstrate more selective absorption of ultrasound than skin, fasciae and subcutaneous fat.[11, 12,15,16,20,25]

The literature reports statistically significant and statistically insignificant increases and decreases in motor and sensory nerve conduction velocities after exposure to therapeutic ultrasound[1-10,32] (Table 3). The disparity in findings of these investigators is difficult to explain, but may be due in part to the technique of application of ultrasound, and nature of the tissues exposed.

The recommended size of treatment area for ultrasound, although variable, is frequently determined by the size of the ultrasound transducer head. Oakley[19] recommended that individual areas up to 1.5 times the area of the ultrasound head be treated for one to two minutes each. Reid and Cummings[24] and Summer and Patrick[18] recommended treatment of an area up to twice the size of the ultrasound head, while Faris[28] suggested an area of three times the ultrasound head. Wadsworth and Chanmugam[11] recommended an area of 50 to 70cm$^2$, depending upon the size of the ultrasound head. Lehmann and De Lateur[14] and Lehmann et al[33] recommended an area of 10cm by 7.5cm, but did not relate this area to the size of the ultrasound head. As is evidenced by these authors, the area of treatment with ultrasound is not very large. Several investigators[5-8,32] however, applied ultrasound to the entire length of the forearm, and examined conduction velocity of the elbow-to-wrist segment of the nerve. This large an area is unlikely to receive an even

TABLE 3

The effects of ultrasound on nerve conduction velocity found by previous investigators



heating effect,[11,14,18,24] which may be a reason why the results obtained by these investigators were inconsistent.

A second factor which may have contributed to the discrepancies in nerve conduction velocities from Table 3 is the anatomical location and course of the nerves which were studied. Several investigators[5-7] insonated the ulnar nerve along the length of the forearm to the wrist. Cosentino et al[32] insonated the median nerve along its length in the forearm. Both of these nerves are covered by muscle in the proximal one-half of the forearm, and become more superficial as they approach the wrist, covered by skin and fasciae.[34] Because these nerves do not lie at a uniform depth or tissue bed along the forearm,[34] the nerves might not have been affected equally along their lengths in the forearm by a single intensity of ultrasound. The observation that ulnar and median nerve conduction velocities decreased following ultrasound treatments might further be explained by the cooling effect of the ultrasound transmission gel over the digital portion of these nerves, which are covered only by skin and fasciae.[4]

The investigators who insonated nerves throughout a smaller area (up to 12 cm long by 6 cm wide) all found increases in nerve conduction velocity, and attributed these increases to the thermal effects of the ultrasound.[1-4,9,18] Esmat[8] treated the ulnar nerve in the forearm, and found increases in nerve conduction velocity at 0.5, 1.0 and 2.0 W/cm$^2$. He did not give measurements of the area of

insonation, however the diagram in his paper appears to demonstrate insonation to the proximal one-half of the forearm. Esmat concluded the increases in nerve conduction velocity were due to the thermal effects of ultrasound.

Farmer[5] suggests the increases in nerve conduction velocity he obtained at intensities of 0.5 and 3.0 W/cm² were due to the heating effects of ultrasound, while at intensities of 1.0, 1.5 and 2.0 W/cm² the mechanical effects overpowered the thermal effects of ultrasound, thus causing a decrease in nerve conduction velocities. Kramer[9] compared the effects of continuous and pulsed ultrasound, placebo ultrasound and infrared radiation on nerve conduction velocity. He concluded the mechanical effects of ultrasound were not significantly operative due to the fact that continuous ultrasound and infrared treatments both produced increases in nerve conduction velocity, while the placebo and pulsed ultrasound treatments produced decreases in nerve conduction velocity. The increased velocities associated with continuous ultrasound and infrared radiation were consistent with increased subcutaneous tissues temperatures, and were therefore attributed to a thermal-heating effect of the ultrasound. Kramer further suggested that the decreases in nerve conduction velocities with pulsed and placebo ultrasound treatments were attributed to the cooling effects of the ultrasound transmission gel. This cooling is attributed to the conduction of heat from the skin surface to the ultrasound transmission gel. Normal external (skin)

temperature is in a range of 28 to 33 degrees Celcius.[38] Ultrasound transmission gel at a normal room temperature of 23 to 25 degrees Celcius would therefore, when applied to the skin, cause cooling via conduction.

**E. Conclusion**

The effects of therapeutic ultrasound have been shown to increase and decrease motor and sensory nerve conduction velocity. The method of application of ultrasound to peripheral nerves appears to affect the changes in conduction velocity following insonation, demonstrating the importance of maintaining a treatment area that is not excessively large. The physical principle that ultrasound frequency is directly related to depth of penetration and absorption has not been clearly demonstrated in the literature, yet is recommended clinically.[11-23] It is evident that a comparison of different ultrasound frequencies applied to a superficially located peripheral nerve might give some indication as to the amount of absorption of ultrasound by the nerve, as indicated by changes in conduction velocity.

## Chapter III

## METHODS AND PROCEDURES

### A. Subjects

Nineteen females ranging in age from 19 to 24 years (mean age 20.8 years) served as subjects for this study. All were informed volunteers who reported no history of neurological trauma or disorders. Only female subjects were used to allow for less variability in the nerve conduction velocities because systematic differences in conduction velocities have been shown to occur between the sexes. Females (on average) demonstrate faster nerve conduction velocities than males.[27]

Nerve conduction data were collected from a ten to thirteen centimeter segment of the ulnar nerve on the medial aspect of the distal segment of the dominant arm of each of the subjects. The literature reports controversy as to whether there is a difference in motor nerve conduction velocities between the dominant and non-dominant arms.[27,34,37] By testing only the dominant arm, any variation of motor nerve conduction velocity that might have occurred between dominant and non-dominant arms was excluded.

All subjects were questioned regarding any history of trauma or neurological disorder affecting their dominant arm. All subjects were given an information sheet and asked to sign a consent form (Appendix A).

**B. Positioning of Subjects**

Treatments, tests and examinations were performed with the subject supine on a treatment couch and the tested arm supported on a table. The tested arm was positioned in approximately seventy degrees shoulder abduction, seventy degrees shoulder lateral rotation, ninety degrees elbow flexion[3,8] and the forearm in mid-position between full pronation and full supination (Figure 2). All joint positions were within the subject's normal active range of motion. The forearm and hand were supported by small pillows in order to eliminate the need for muscular effort in maintaining the test/treatment position.

FIGURE 2: Position of the subject during experimental procedure

## C. Apparatus

### Electromyograph (EMG)

A TECA TE-42 Electromyograph was used to perform the motor and sensory nerve conduction studies (Figure 3). The EMG stimulus was a rectangular pulse of 0.1 milliseconds duration, delivered at a supramaximal intensity at a frequency of two pulses per second.[27] The EMG stimulus was applied with a TECA 9523-1 bipolar stimulating electrode. The low and high frequency cut-offs for motor and sensory responses were 1.6 and 3,200 cycles per second, and 32 and 1,600 cycles per second, respectively.

FIGURE 3: TECA TE-42 ELECTROMYOGRAPH

The EMG stimulator, surface disc (motor) and ring (sensory) and ground electrodes are shown in Figure 4. Permanent recordings of the EMG tracings were recorded on Kodak Linagraphic direct print photographic paper.

FIGURE 4: EMG motor electrodes, ground electrode, bipolar stimulator, sensory ring electrodes

**Ultrasound**

Ultrasound treatments were administered using a Sonacel Multiphon MK II Ultrasound unit, from Rank Stanley Cox Limited, Hertfordshire, England (Figure 5). This ultrasound unit has three separate sound-heads, each delivering a different ultrasound frequency: 0.75 Megahertz (MHz), 1.5 MHz and 3.0 MHz. The transmission coupling agent used was Ultraphonic Conductivity Gel, Pharmaceutical Innovations Inc., Newark, New Jersey.

FIGURE 5: Sonacel Multiphon MK II Ultrasound Unit and Ultraphonic Conductivity Gel

**Timer**

All ultrasound treatments during the experimental procedure were timed using a Gra-lab Timer, model 171 (Figure 6). This procedure eliminated any error that may have occurred using only the spring-wound timer on the ultrasound unit.

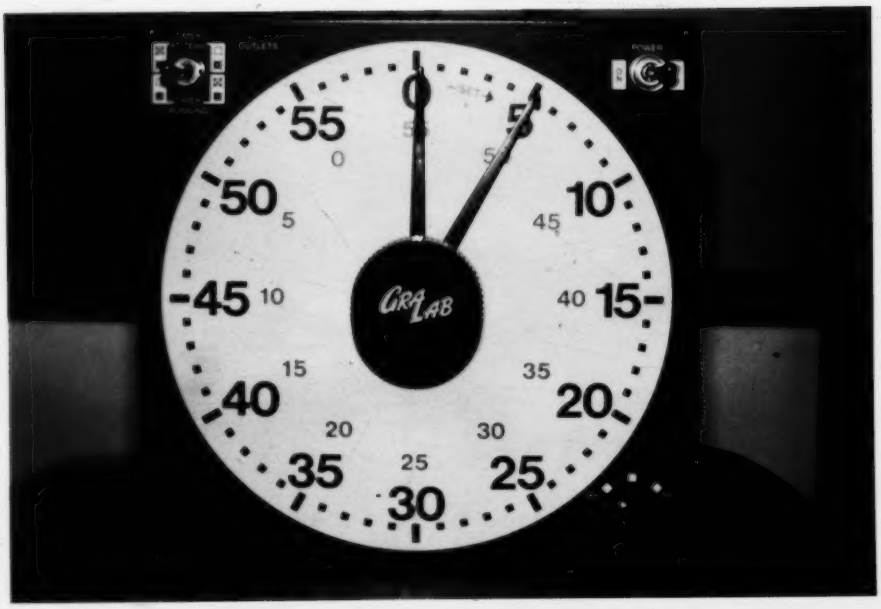



FIGURE 6: Gra-lab Timer, model 171

**D. Calibration of the Ultrasound**

Calibration of frequencies and intensity of the Rank Stanley Cox Sonacel Multiphon MK II ultrasound unit was carried out prior to the experimental procedures by a technician from Biomedical Inspection Services Limited, Edmonton, Alberta. Calibration was performed using a Russian Ultraschalleistungmessgerat NMY-3 water balance calibration device (see Appendix B for details). Calibration was checked by the investigator mid-way through and at the end of the experimental procedure.

**E. Experimental Procedure**

On their initial visit to the test laboratory, the subjects were given a full explanation of the test procedures, and were asked to sign a consent form (Appendix A). Each subject was then assigned to a randomly selected order of ultrasound treatments according to ultrasound frequency (Appendix C). Each subject acted as her own control (0.0 MHz frequency) by receiving 0.0 $W/cm^2$ intensity of ultrasound. There was a minimum of twenty-four hours between test procedures.

Once the subject was positioned comfortably supine on the treatment couch, the dominant arm was exposed from the upper arm to the fingers. The medial aspect of the distal segment of the arm, medial and dorsal aspects of the hand and fifth finger were cleansed with isopropyl alcohol. The skin of the fifth finger was lightly debrided with fine sandpaper to ensure effective pick-up from the two sensory ring electrodes.

The motor EMG surface disc electrodes were placed two centimeters apart (mounted on a wooden bar), with the proximal electrode placed over the muscle belly of abductor digiti minimi. The sensory EMG surface ring electrodes were placed around the fifth finger: one electrode distal to the distal interphalangeal joint, and one electrode proximal to the proximal interphalangeal joint. The ground EMG surface disc electrode was placed over the dorsum of the hand. All

electrodes were securely held in position with adhesive tape (Figure 7).

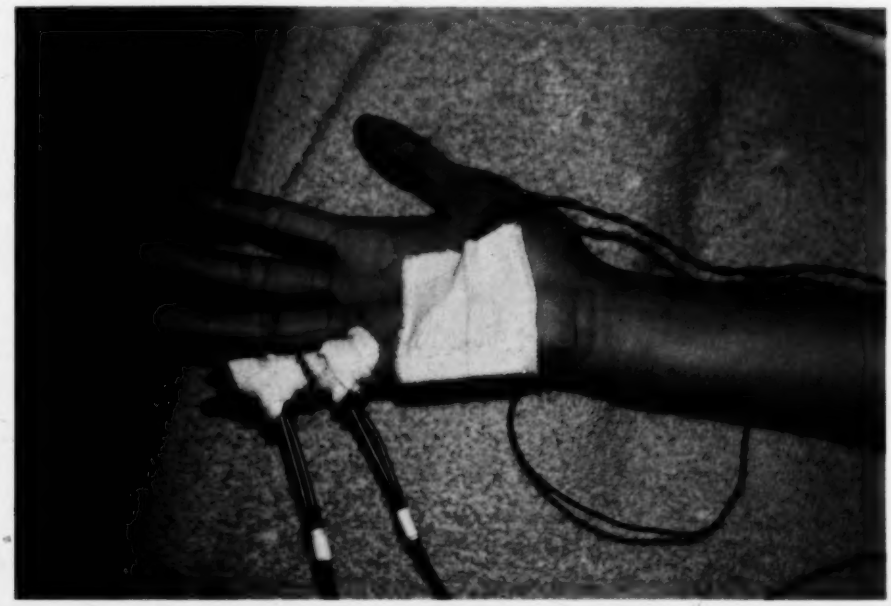


FIGURE 7: Position of motor, sensory and ground EMG electrodes

The EMG stimulator was placed over the ulnar nerve in the ulnar notch at the elbow. The position of the stimulator at which the greatest motor and sensory action potentials were observed on the oscilloscope was marked with permanent ink. The course of the ulnar nerve was followed proximally along the medial aspect of the arm, and the point of stimulation at which the greatest motor and sensory action potentials were observed on the oscilloscope was marked with permanent ink. The distance between the proximal and distal stimulation sites was ten to thirteen centimeters. Two

parallel lines, approximately three centimeters apart, were drawn between the proximal and distal stimulation sites, indicating the course of the nerve and outlining where the ultrasound treatment would be applied (Figure 8).

**Motor and Sensory EMG Recordings**

Motor and sensory EMG recordings were taken by stimulating both the proximal and distal stimulation sites (Figures 9, 10). A permanent record was taken of the responses by depressing a foot switch which took a picture of the EMG oscilloscope tracing on fibre optic paper. Motor and sensory nerve conduction data were collected at one minute pre-treatment, immediately prior to treatment, immediately following treatment, and one minute post-treatment.

FIGURE 8: Proximal and distal EMG stimulation sites

FIGURE 9: EMG stimulation at the proximal site

FIGURE 10: EMG stimulation at the distal site

**Ultrasound Treatment**

Each subject received five minutes of ultrasound per treatment session at an intensity of 1.5 W/cm², continuous mode. The five minute treatment time and 1.5 W/cm² intensity are both within recommended therapeutic ranges.[11,12,14,16] The ultrasound frequencies used were 0.75 MHz, 1.5 MHz, 3.0 MHz and 0.0 MHz (control), and were assigned to subjects in a random order (Appendix C). Ultrasound transmission gel was applied to the area between the two EMG stimulation sites, and ultrasound was administered to the same area (where the ulnar nerve is covered by skin and fasciae[34]) using a parallel stroking technique, covering the area at approximately three centimeters per second[11] (Figure 11). Immediately following the ultrasound treatment, the transmission gel was wiped off the arm, and motor and sensory nerve conduction data were collected from both EMG stimulation sites. Nerve conduction data were collected again at one minute post-ultrasound treatment.

All treatments, tests and examinations were conducted in a room temperature range of 23 to 25 degrees Celcius, with doors, windows and ventilation ducts closed so as to limit air currents, thus maintaining a stable temperature. All treatments, tests and examinations were conducted during the day in a bright room with large windows. The overhead fluorescent lights were turned off to eliminate any possible electrical interference which could be picked up by the electromyograph.

FIGURE 11: Ultrasound treatment

**F. Ethical Considerations**

The potential risks of any harm coming to any of the subjects was very low. The ultrasound treatment is innocuous, with perhaps only a mild sensation of warmth over the treatment area experienced by the subjects. The dosage to be used (1.5 W/cm² for 5 minutes continuous mode) was well within the recommended therapeutic range of ultrasound, and well below the maximum output intensity (3.0 W/cm²) of the ultrasound unit.

The motor and sensory nerve conduction velocity testing required a brief electrical stimulus to be applied to the ulnar nerve over the medial aspect of the distal segment of

the arm and at the ulnar notch at the elbow. This stimulation produces a buzzing sensation where the stimulus is applied, which may cause momentary mild discomfort.

**G. Statistical Procedures**

Ultrasound frequency and nerve conduction velocity data were examined using a two way analysis of variance with repeated measures on both factors.[39] A Tukey multiple comparison of means test was employed to compare selected means.[40] Pearson-Product Moment Correlation Coefficients[39] were calculated for the one minute pre-treatment and immediately pre-treatment data for motor and sensory nerve conduction velocities for all ultrasound frequencies. The correlation coefficients were calculated to determine the investigator's reliability in measuring nerve conduction velocity.

## Chapter IV

## RESULTS

The major purpose of the study was to determine the effects of different frequencies of therapeutic ultrasound on motor and sensory ulnar nerve conduction velocity. Nineteen healthy, informed female volunteers, with no known history of neurological trauma or disease were examined, with only the subject's dominant arm being tested. The age range was from 19 to 24 years (mean age 20.8 years). Results and discussion are based on the effects of four frequencies of therapeutic ultrasound (0.0 MHz, 0.75 MHz, 1.5 MHz and 3.0 MHz) on motor and sensory ulnar nerve conduction velocity.

There were significant relationships in motor and sensory conduction velocities observed among the four ultrasound frequencies at one minute and immediately before ultrasound application. Table 4 shows the correlations between the one minute and immediate pre-treatment motor and sensory nerve conduction velocities, based on the mean velocities obtained for each frequency. All correlation coefficients were statistically significant at the $p < 0.001$ level. The Pearson-Product Moment Correlation Coefficients were calculated in order to determine the investigator's reliability in measuring nerve conduction velocities.

TABLE 4

Pearson Correlation Coefficients Between One Minute and Immediate Pre-Treatment Nerve Conduction Velocities for Different Ultrasound Frequencies

| Criterion Measure | Ultrasound Frequency (MHz) | | | |
|---|---|---|---|---|
| | 0.0 | 0.75 | 1.5 | 3.0 |
| MNCV* | 0.89 | 0.95 | 0.89 | 0.94 |
| SNCV** | 0.93 | 0.82 | 0.80 | 0.87 |

* Motor Nerve Conduction Velocity
** Sensory Nerve Conduction Velocity
All values were statistically significant ($p < 0.001$)

Tables 5 and 6, respectively, show the motor and sensory nerve conduction velocity means and standard deviations, measured at one minute and immediately pre-treatment, and immediately and one minute post-treatment, with different frequencies of ultrasound. Figures 12 and 13, respectively, are graphic representations of motor and sensory nerve conduction velocities before and after application of different ultrasound frequencies. Table 7 indicates the mean change (immediate post-treatment conduction velocity minus immediate pre-treatment conduction velocity) in motor and sensory nerve conduction velocities following application of ultrasound at different frequencies.

The two way analysis of variance tests with repeated measures on both factors demonstrated statistically significant main effects for frequency, time (pre and post treatment) and interaction for both motor and sensory nerve conduction velocities ($p < 0.001$). The analysis of variance results for motor and sensory nerve conduction velocities are presented in Tables 8 and 9, respectively.

TABLE 5

Mean and Standard Deviations of One Minute and Immediate Pre and Post-Treatment Motor Nerve Conduction Velocities for each Ultrasound Frequency

| | MOTOR NERVE CONDUCTION VELOCITY (m/s) | | | |
|---|---|---|---|---|
| Ultrasound Frequency (MHz) | One Minute Pre -Treatment | Immediately Pre -Treatment | Immediately Post -Treatment | One Minute Post -Treatment |
| 0.0 | 61.54 (4.20)* | 62.39 (4.30) | 58.52 (4.60) | 58.24 (5.49) |
| 0.75 | 60.90 (5.35) | 61.51 (5.03) | 63.14 (4.99) | 63.38 (5.39) |
| 1.5 | 60.42 (3.99) | 61.08 (4.15) | 63.11 (3.87) | 62.78 (3.98) |
| 3.0 | 61.77 (3.93) | 61.72 (4.94) | 67.54 (4.81) | 66.79 (5.33) |

* (standard deviation)

TABLE 6

Mean and Standard Deviation of One Minute and Immediate Pre and Post-Treatment Sensory Nerve Conduction Velocities for each Ultrasound Frequency

| Ultrasound Frequency (MHz) | SENSORY NERVE CONDUCTION VELOCITY (m/s) One Minute Pre -Treatment | Immediately Pre -Treatment | Immediately Post -Treatment | One Minute Post -Treatment |
|---|---|---|---|---|
| 0.0 | 65.12 (4.53)* | 65.24 (4.56) | 61.54 (4.59) | 61.04 (5.13) |
| 0.75 | 63.07 (3.94) | 63.73 (4.04) | 66.56 (5.16) | 65.80 (4.83) |
| 1.5 | 64.43 (3.35) | 65.05 (4.01) | 66.14 (3.85) | 65.57 (3.47) |
| 3.0 | 65.27 (2.86) | 65.19 (4.23) | 70.36 (4.55) | 69.05 (4.44) |

* (standard deviation)

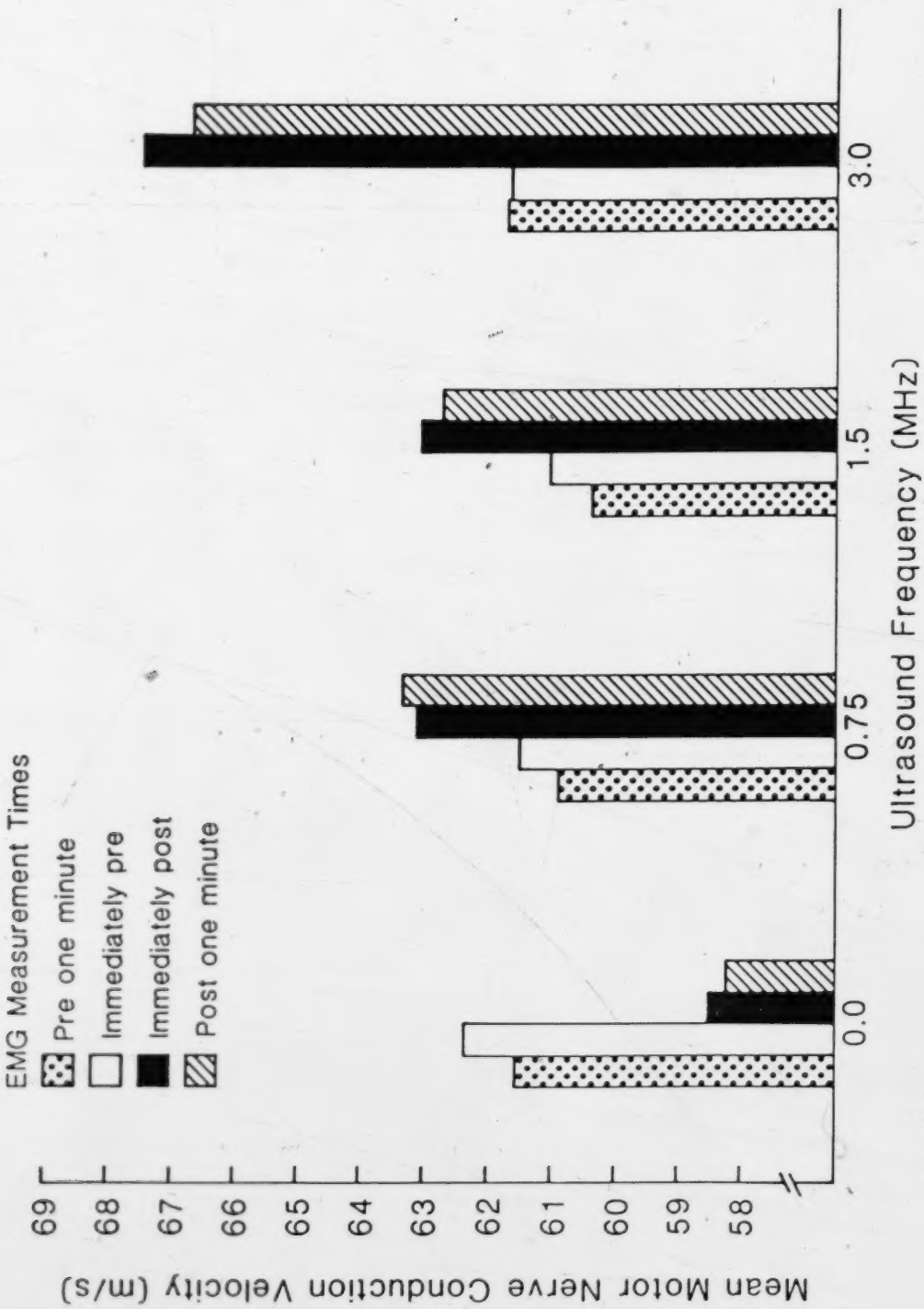



FIGURE 12: Mean motor nerve conduction velocities before and after ultrasound of different frequencies

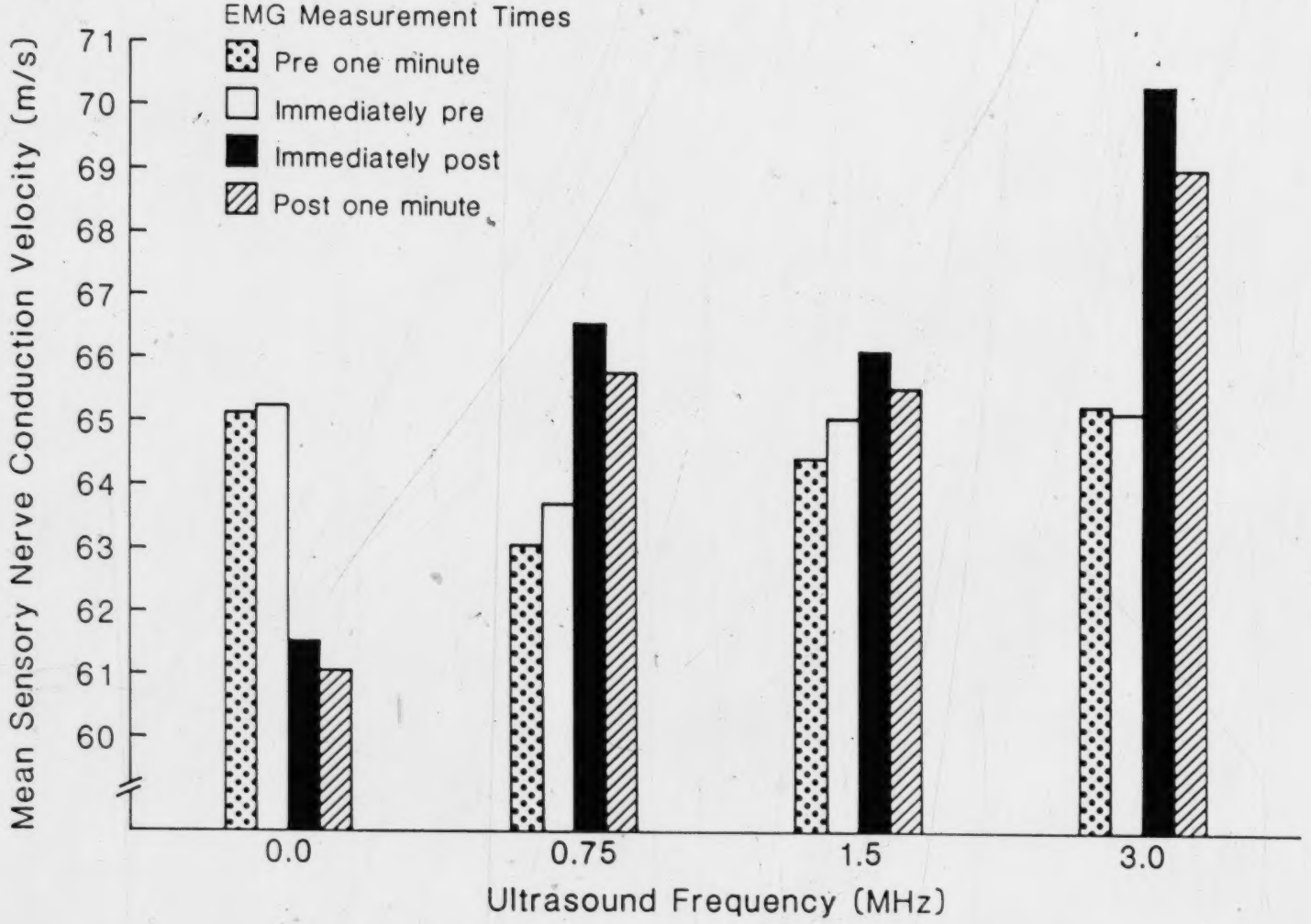



FIGURE 13: Mean sensory nerve conduction velocities before and after ultrasound of different frequencies

TABLE 7

Changes in Motor and Sensory Nerve Conduction Velocity Following Application of Ultrasound at Different Frequencies

| Ultrasound Frequency (MHz) | Change in Motor Nerve Conduction Velocity (m/s) | Change in Sensory Nerve Conduction Velocity (m/s) |
|---|---|---|
| 0.0 | -3.87 | -3.70 |
| 0.75 | +1.63 | +2.83 |
| 1.5 | +2.03 | +1.09 |
| 3.0 | +5.82 | +5.17 |

"+" denotes increase "-" denotes decrease

TABLE 8

Analysis of Variance for Motor Nerve Conduction Velocity

| Source of Variation | Sum of Squares | Degrees of Freedom | Mean Squares | F Ratio |
|---|---|---|---|---|
| Frequency Main Effects | 707.254 | 3 | 235.751 | 8.26* |
| Frequency X Subjects Within Groups | 1541.624 | 54 | 28.549 | |
| Time Main Effects | 189.202 | 3 | 63.067 | 14.38* |
| Time X Subjects Within Groups | 236.895 | 54 | 4.387 | |
| Frequency X Time Interaction | 806.880 | 9 | 89.653 | 33.20* |
| Frequency X Time X Subjects Within Groups | 437.481 | 162 | 2.701 | |

* denotes significance at $p < 0.001$

TABLE 9

Analysis of Variance for Sensory Nerve Conduction Velocity

| Source of Variation | Sum of Squares | Degrees of Freedom | Mean Squares | F Ratio |
|---|---|---|---|---|
| Frequency Main Effects | 697.546 | 3 | 232.515 | 8.28* |
| Frequency X Subjects Within Groups | 1516.720 | 54 | 28.087 | |
| Time Main Effects | 123.003 | 3 | 41.001 | 8.62* |
| Time X Subjects Within Groups | 256.816 | 54 | 4.756 | |
| Frequency X Time Interaction | 750.886 | 9 | 83.432 | 29.80* |
| Frequency X Time X Subjects Within Groups | 453.488 | 162 | 2.799 | |

* denotes significance at $p < 0.001$

Following the demonstration of significant ($p < 0.001$) main effects on the analysis of variance, Tukey post hoc tests were employed to compare the six pairs of row means calculated at each ultrasound frequency for motor and sensory nerve conduction velocities. Table 10 illustrates the comparison of the six pairs of frequency on motor conduction velocity, one of which (0.0 MHz vs 3.0 MHz) was significant ($p < 0.01$). Table 11 illustrates the comparison of the six pairs of frequency on sensory conduction velocity, again one of which (0.0 MHz vs 3.0 MHz) was significant ($p < 0.01$). Tables 12 and 13, respectively, illustrate the comparisons of the six pairs of pre and post-treatment measurements of motor and sensory conduction velocities averaged over frequency. Of the six pairs of pre and post-treatment motor conduction velocities, three pairs (pre 1 vs post 0; pre 1 vs post 1; pre 0 vs post 0) demonstrated significance at the $p < 0.01$ level, and one pair (pre 0 vs post 1) demonstrated significance at the $p < 0.05$ level (Table 12). Two of the six pairs of pre and post-treatment sensory conduction velocities demonstrated significance, one pair (pre 1 vs post 0) at the $p < 0.01$ level, and one pair (pre 0 vs post 0) at the $p < 0.05$ level (Table 13).

The interaction effects for motor and sensory nerve conduction velocities are graphically depicted in Figures 14 and 15, respectively.

TABLE 10
Tukey Test Comparison Between Levels of
Ultrasound Frequency on Motor Nerve Conduction Velocity

| Levels of Frequency | Means | Critical Value | Probability |
|---|---|---|---|
| f0 vs f1* | 60.171-62.235 | -3.37 | NS |
| f0 vs f2 | 60.171-61.848 | -2.74 | NS |
| f0 vs f3 | 60.171-64.451 | -6.98 | < 0.01 |
| f1 vs f2 | 62.235-61.848 | 0.63 | NS |
| f1 vs f3 | 62.235-64.451 | -3.62 | NS |
| f2 vs f3 | 61.848-64.451 | -4.25 | NS |

TABLE 11
Tukey Test Comparison Between Levels of
Ultrasound Frequency on Sensory Nerve Conduction Velocity

| Levels of Frequency | Means | Critical Value | Probability |
|---|---|---|---|
| f0 vs f1* | 63.237-64.790 | -2.55 | NS |
| f0 vs f2 | 63.237-65.295 | -3.39 | NS |
| f0 vs f3 | 63.237-67.468 | -6.96 | < 0.01 |
| f1 vs f2 | 64.790-65.295 | -0.83 | NS |
| f1 vs f3 | 64.790-67.468 | -4.41 | NS |
| f2 vs f3 | 65.295-67.468 | -3.57 | NS |

* f0 = 0.0 MHz
f1 = 0.75 MHz
f2 = 1.5 MHz
f3 = 3.0 MHz

TABLE 12
Tukey Test Comparison Between Pre and Post-Treatment
Motor Nerve Conduction Velocities

| Levels of Times | Means | Critical Value | Probability |
|---|---|---|---|
| pr1 vs pr0* | 61.156-61.674 | -2.16 | NS |
| pr1 vs po0 | 61.156-63.078 | -8.00 | < 0.01 |
| pr1 vs po1 | 61.156-62.797 | -6.83 | < 0.01 |
| pr0 vs po0 | 61.674-63.078 | -5.84 | < 0.01 |
| pr0 vs po1 | 61.674-62.797 | -4.67 | < 0.05 |
| po0 vs po1 | 63.078-62.797 | 1.17 | NS |

TABLE 13
Tukey Test Comparison Between Pre and Post-Treatment
Sensory Nerve Conduction Velocities

| Levels of Times | Means | Critical Value | Probability |
|---|---|---|---|
| pr1 vs pr0* | 64.473-64.801 | -1.31 | NS |
| pr1 vs po0 | 64.473-66.150 | -6.71 | < 0.01 |
| pr1 vs po1 | 64.473-65.365 | -3.57 | NS |
| pr0 vs po0 | 64.801-66.150 | -5.39 | < 0.05 |
| pr0 vs po1 | 64.801-65.365 | -2.26 | NS |
| po0 vs po1 | 66.150-65.365 | 3.14 | NS |

pr1 = one minute pre-treatment
pr0 = immediately pre-treatment
po0 = immediately post-treatment
po1 = one minute post-treatment

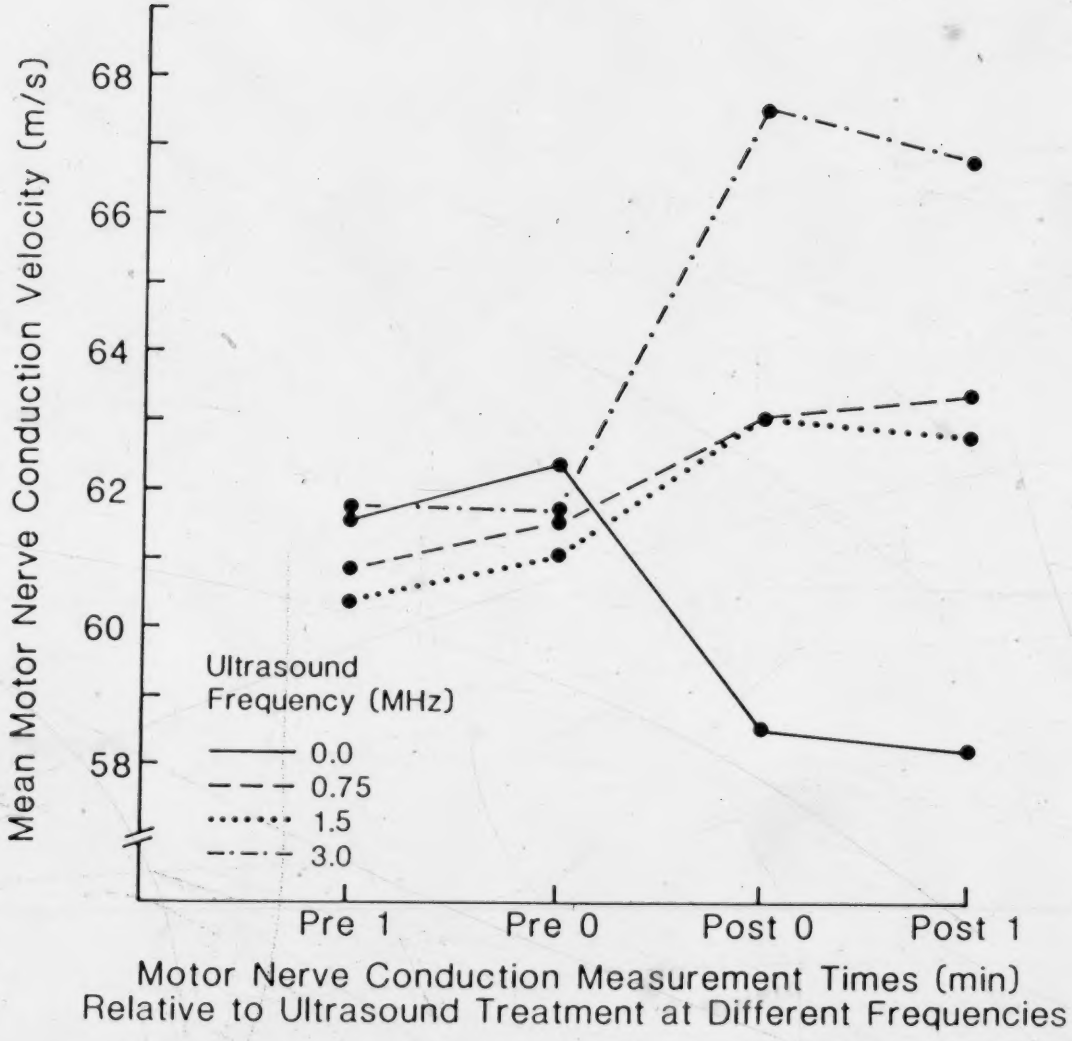



FIGURE 14: Graphic representation of interaction effects for motor nerve conduction velocities

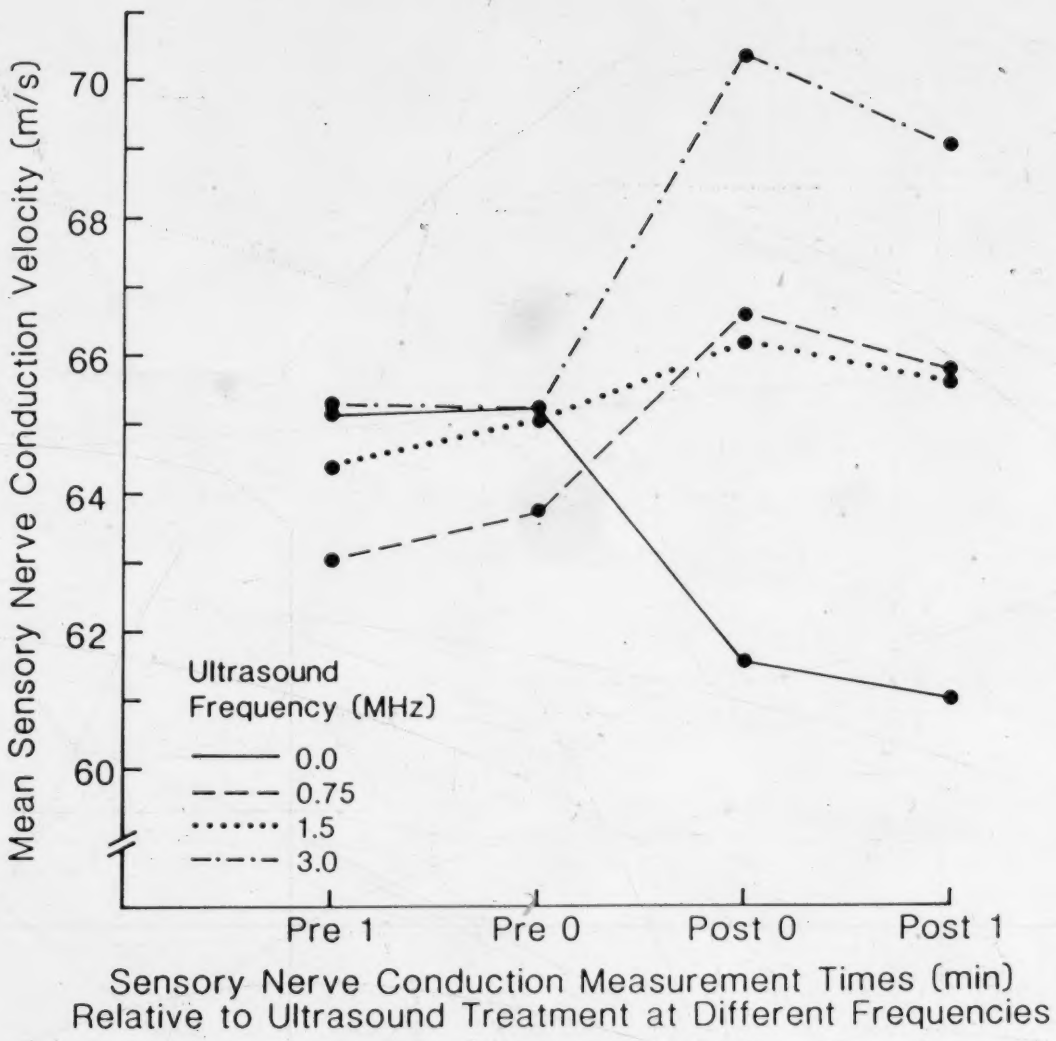



FIGURE 15: Graphic representation of interaction effects for sensory nerve conduction velocities

## Chapter V

## DISCUSSION

The analysis of variance tests for both motor and sensory ulnar nerve conduction velocities demonstrated statistically significant effects for frequency, time and interaction, as illustrated in Tables 8 and 9.

There was a significant main effect over time for both motor and sensory conduction velocities. This finding is in agreement with several previous studies studies[1-10,32] which reported changes in nerve conduction velocities following the application of ultrasound. There is variability in these studies relative to the pre-treatment and post-treatment times of measurement of nerve conduction velocities. The majority of investigators[1-5,7,9,10,32] measured nerve conduction velocities immediately prior to and immediately following application of ultrasound. In contrast, Esmat[8] and Madsen and Gersten[4] measured conduction velocities immediately pre-treatment and waited fifteen and three minutes, respectively, before measuring post-treatment conduction velocities.

The post hoc Tukey tests comparing pre and post-ultrasound treatment motor nerve conduction velocities (Table 12) demonstrated significant differences between four pairs of means. The one minute pre versus immediate post-treatment, one minute pre versus one minute

post-treatment and immediate pre versus immediate post-treatment times were significant at $p < 0.01$, while the immediate pre versus one minute post-treatment time was significant at $p < 0.05$. These results are attributed to the effects of ultrasound on nerve conduction velocity, and are consistent with previous reports[5-10] which found significant differences in motor nerve conduction velocities post ultrasound application. Kramer[9,10] and Esmat[8] demonstrated increases in conduction velocity, while Farmer[5], Madsen and Gersten[4] and Zankel[7] demonstrated decreases in conduction velocity.

The two pairs of means that demonstrated non-significant changes in motor nerve conduction velocity were the one minute pre versus immediate pre-treatment, and immediate post versus one minute post-treatment times. The one minute pre versus immediate pre-treatment measurement times would not be expected to demonstrate significant changes in conduction velocities because no treatment was administered[4,7,10] The immediate post versus one minute post-treatment measurement times lack of significant change indicates that the effects of the ultrasound on nerve conduction velocity remained relatively constant for the one minute period between post-treatment measurements.[7,10]

Table 13 illustrates the Tukey post hoc tests comparing pre and post ultrasound treatment sensory nerve conduction velocities. Two pairs of means were statistically significant: the pre one minute versus immediate

post-treatment ($p < 0.01$) and immediate pre versus immediate post-treatment ($p < 0.05$) conduction velocities. These changes in sensory nerve conduction velocities after ultrasound application are consistent with previous studies.[1-4] Although the two other pre versus post-treatment pairwise comparisons (one minute pre versus one minute post, and immediate pre versus one minute post-treatment) did not demonstrate significant differences, their changes were in the expected direction.

The one minute pre versus immediate pre-treatment comparison demonstrated no significant change because no treatment was administered between measurements.[4,7,10] The immediate post versus one minute post-treatment comparison also demonstrated no significant changes due to the effects of ultrasound on nerve conduction velocity remaining relatively constant for the one minute period between post-treatment measurements.[7,10]

There was a significant main effect for ultrasound frequency for both motor and sensory nerve conduction velocities, indicated by the changes in conduction velocities following insonation at different frequencies. To the investigator's knowledge, this has not been previously reported in the literature. The post hoc Tukey tests (Figures 14 and 15) demonstrated the significant main effect for frequency was due to the large differences in post ultrasound nerve conduction velocities between the 0.0 MHz frequency and the other three frequencies (0.75 MHz, 1.5 MHz

and 3.0 MHz). The largest difference occurred between 0.0 MHz and 3.0 MHz. This is attributed to the different effects these two frequencies had on the ulnar nerve during insonation.

Both motor and sensory ulnar nerve conduction velocities decreased significantly following the administration of placebo (0.0 MHz) ultrasound. This is attributed to the cooling effect of the ultrasound transmission gel on the skin, fasciae and subcutaneously located ulnar nerve. This finding is in agreement with several previous studies which found decreases in nerve conduction velocities with no emission of ultrasound energy.[4,9,10] Madsen and Gersten[4] and Cosentino et al[32] found decreases in nerve conduction velocities following placebo ultrasound, but did not discuss the possible mechanisms for these reductions. Kramer[4,9,10] concluded the decreases in nerve conduction velocities were due to the cooling effects of the ultrasound transmission gel when he observed concomitant decreases in subcutaneous tissue temperatures in the area of insonation. In the present study, 18 of 19 subjects demonstrated decreases in motor (mean decrease 3.87 m/s) and sensory (mean decrease 3.70 m/s) nerve conduction velocities following insonation with the 0.0 MHz frequency.

Insonation of the ulnar nerve at the 3.0 MHz frequency produced the greatest increases in post-treatment motor and sensory nerve conduction velocities (Figures 14 and 15). To

the investigator's knowledge, the effects of 3.0 MHz ultrasound on nerve conduction velocity has not been previously investigated. The reasons for the large increases in motor and sensory conduction velocities following insonation are assumed to be due to the absorption and depth of penetration characteristics of 3.0 MHz ultrasound. The amount of ultrasound absorption is primarily dependent on two factors: (i) the frequency of the ultrasound; and (ii) the nature of the medium to which it is applied.

The higher the frequency of ultrasound, the shorter the wavelength, the more superficial the absorption, and the less the depth of penetration.[11-16,20] Low frequency, long wavelength ultrasound travels further in human tissue than high frequency short wavelength ultrasound.[11-22] This is due to absorption of the ultrasound as it enters the tissues. In the present study, the greatest difference in nerve conduction velocities following ultrasound application to the superficially (subcutaneously) located ulnar nerve occurred between the 0.0 MHz and 3.0 MHz frequencies. The significant increases in motor and sensory nerve conduction velocities following insonation are not surprising because of the superficial absorption of 3.0 MHz ultrasound and the high absorption rate of nerve tissue. Tables 10 and 11 show that the 0.75 MHz and 1.5 MHz ultrasound frequencies did demonstrate immediate post-treatment increases in conduction velocities, but these changes were not statistically significant. It is assumed this occurred because the lower

ultrasound frequencies have longer wavelengths, and absorption of the ultrasound energy occurs at a deeper level,[11-22] thus the majority of the ultrasound energy was absorbed deep to the ulnar nerve.

The analysis of variance tests demonstrated a significant frequency X time interaction effect for both motor and sensory components of the ulnar nerve (Tables 8 and 9). The Tukey post hoc tests represented graphically in Figures 14 and 15 demonstrate interaction among all frequencies occurred between the immediate pre and immediate post ultrasound treatment measurements of nerve conduction velocity. The interaction is attributed to the effects of the ultrasound (0.75 MHz, 1.5 MHz and 3.0 MHz) and placebo ultrasound (0.0 MHz) treatments. Visual inspection of Figures 14 and 15 shows the most significant interaction occurred between the immediate pre and immediate post-ultrasound treatments for the 0.0 MHz and 3.0 MHz frequencies for both motor and sensory velocities, respectively. This demonstrates that the 0.0 MHz and 3.0 MHz ultrasound frequencies produced the largest differences in post-ultrasound treatment nerve conduction velocities for both motor and sensory components of the ulnar nerve. These differences were expected because of the opposite effects 0.0 MHz and 3.0 MHz ultrasound treatment have on subcutaneous peripheral nerves.

Several studies have demonstrated significant decreases in nerve conduction velocities following application of

placebo ultrasound.[4,6,9,10,32] Although no literature has reported the effects of 3.0 MHz ultrasound on nerve conduction velocity, several authors have suggested that high frequency ultrasound will be absorbed superficially,[11-22] and that peripheral nerves readily absorb ultrasound'', [12,15,16,20,25] The results of the present study, demonstrating significant decreases in motor and sensory nerve conduction velocities following 0.0 MHz (placebo) ultrasound, and significant increases in motor and sensory nerve conduction velocities following 3.0 MHz ultrasound, are supported by this literature.

The differences between the conduction velocities observed at 0.0 MHz and 3.0 MHz ultrasound occurred due to the opposite effects each frequency had on the ulnar nerve. The large decrease in conduction velocities observed with 0.0 MHz may have confounded the effects, thereby making the overall difference larger than if the 0.0 MHz results had not been included in the statistical analyses. The inclusion of the decreases observed with 0.0 MHz ultrasound in the statistical analyses may have contributed to the lack of significant differences observed among all other pair-wise comparisons of ultrasound frequencies.

**A. Clinical Implications**

It has been suggested by several authors that different therapeutic ultrasound frequencies should be used for the treatment of lesions found at different depths of

tissue.[11-22] These suggestions are based on the physical principle that different ultrasound frequencies have different sound-beam wavelengths, and that different wavelengths travel to different depths in human tissue before being absorbed. The trends in the present study of increasing nerve conduction velocity with increasing ultrasound frequency tend to support the premise that high frequency (3.0 MHz) ultrasound is more superficially absorbed than low frequency ($\leq$ 1.0 MHz) ultrasound, and provides empirical support for the clinical recommendation that deep tissue lesions be treated with low frequency ultrasound and more superficially located lesions be treated with high frequency ultrasound.[11-22] However, it must be realized that the tissue examined in the present study was the ulnar nerve located superficially in the arm, and because this tissue is not representative of all human tissues, this clinical recommendation is offered with some caution. Further empirical investigation is needed to provide clinical validity to this contention.

## Chapter VI

## SUMMARY AND CONCLUSIONS

The purpose of the study was to determine the effects of different frequencies of therapeutic ultrasound on motor and sensory ulnar nerve conduction velocity. A sample of nineteen females was used, with examinations and tests conducted only on the dominant arm. Each subject was tested on four separate occasions, one for each frequency of ultrasound used in the study.

The testing procedure involved taking two pre-treatment motor and sensory nerve conduction velocity measurements, applying a five minute ultrasound treatment at a fixed intensity and randomly chosen frequency, and two post-treatment motor and sensory nerve conduction velocity tests.

Different scores, post ultrasound treatment minus pre ultrasound treatment motor and sensory nerve conduction velocities were analyzed to determine if significant differences existed due to the different frequencies of ultrasound treatment. A two way analysis of variance (two groups, with repeated measures over four ultrasound frequencies and four nerve conduction measurement times) was used to examine different values of motor and sensory nerve conduction velocities, as determined by nerve conduction velocity measurements taken at two pre and two

post-treatment times (one minute and immediately pre, and immediately and one minute post).

Further analysis on the significant time, frequency and interaction effects was completed using a Tukey multiple comparison test on the mean values of the raw scores obtained from the electromyograph tracings.

Pearson-Product Moment Correlation Coefficients were calculated to determine whether there was a significant relationship between the one minute and immediate pre-treatment motor and sensory nerve conduction velocity measurements. These Coefficients were calculated for each ultrasound frequency group, and were done in order to determine the investigator's reliability in measuring nerve conduction velocities.

**A. Conclusions**

On the basis of the present study, the following conclusions were made:

1. There were significant changes in both motor and sensory nerve conduction velocities following application of ultrasound with four different frequencies. Increases occurred at 0.75, 1.5 and 3.0 MHz; decreases occurred at 0.0 MHz. These findings support research hypotheses (i) and (ii).
2. There were significant differences between the effects of 0.0 MHz and 3.0 MHz ultrasound on

both motor and sensory nerve conduction velocities.

3. Although the changes were in the expected direction, there were no significant differences between the effects of all other pair-wise comparisons of ultrasound frequencies on motor and sensory nerve conduction velocities. These findings do not support research hypothesis (iii).

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# APPENDIX A

FORMS USED IN RESEARCH PROJECT

# INFORMED CONSENT FOR INVESTIGATIVE STUDY

## EVALUATION OF THE EFFECTS OF THERAPEUTIC ULTRASOUND FREQUENCIES ON NERVE CONDUCTION VELOCITY

### Outline of Procedures (retained by the subjects)

Ultrasound is a commonly used therapeutic modality in physical therapy departments and clinics. Many of the physiological effects of ultrasound are based on its thermal or heating effect. Many scientific studies have demonstrated a thermal effect on motor and sensory nerve conduction velocities, however these studies used ultrasound machines with one fixed frequency. The literature purports that with different frequencies, thermal effects should occur at different subcutaneous tissue depths. This study will attempt to compare motor and sensory nerve conduction velocities obtained using different frequencies of therapeutic ultrasound.

The study in which you are being requested to participate will apply a clinical ultrasound treatment to the inside of your arm, just above the elbow, and measure changes in nerve conduction velocity of a nerve which courses through the area to which the ultrasound was applied. You are requested to participate in four ultrasound

sessions, each approximately 30 minutes in length, and at least one day apart from each other. The ultrasound application will last 5 minutes, and you will note nothing more than a possible slightly warm sensation on your arm.

The motor and sensory nerve conduction velocity determination utilizes a mild intensity electrical stimulation applied to the nerve in your upper arm. You will feel a buzzing sensation and perhaps mild discomfort, and your little finger will twitch due to the stimulation. This procedure is associated with virtually no danger, and every safety precaution has been monitored by the investigator.

Treatment will be administered in the lying position with the arm being treated (dominant arm) positioned comfortably on pillows. You have the right to withdraw from participation at any time during the study.

No records or photographs which would permit your identification will be made public without your written consent.

In the event any questions arise concerning the study, please feel free to contact the principle investigator, Mr. G.A. Rennie (432-5973).

INFORMED CONSENT FORM FOR INVESTIGATIVE STUDY

EVALUATION OF THE EFFECTS OF THERAPEUTIC ULTRASOUND FREQUENCIES ON NERVE CONDUCTION VELOCITY

Subject Consent (retained by investigator)

I , do herby agree to participate in the study entitled "Evaluation of the Effects of Therapeutic Ultrasound Frequencies on Nerve Conduction Velocity" to be conducted by Mr. G.A. Rennie and/or his designate(s). The nature of this study has been explained to me and I understand that it is not intended as a form of remedial treatment. I am not presently suffering from any pathology or disease. I have been advised that I may withdraw from participation at any time.

..... .....
Subject's signature Date

..... .....
Address Phone

.....

# APPENDIX B

## CALIBRATION OF EQUIPMENT

**Calibration of the Ultrasound Unit**

Calibration of the three frequencies and intensity for each frequency was carried out by a technician from Biomedical Inspection Services Limited, Edmonton, Alberta. The calibration device used was the Russian Ultraschalleistungmessgerat NMY-3 water balance. The water container of the NMY-3 unit was filled to the water mark with distilled water, and left to sit for two days to allow any gas bubbles to escape. The ultrasound head was covered on its outer circumference by foam padding so that the ultrasound head fitted snugly into the opening on the top of the water container. In order to ensure the face of the ultrasound head was parallel to the water line, a small spirit level was placed on the back of the ultrasound head (Figure 16). The ultrasound unit was turned on, and the ARR switch on the calibration unit was pushed down so as to release the metal deflection plate. Both the balance deflection indicator and total watts output indicator were set at zero, as per instructions in the NMY-3 manual.

Calibration of ultrasound frequency was carried out as per instructions from Rank Stanley Cox Limited, manufacturers of the ultrasound unit. This procedure required turning up the ultrasound intensity until the water balance needle deflected away from the vertical line. Adjustment of the frequency pot in the back of the ultrasound unit was performed until the needle demonstrated maximum deflection from the vertical line. Once the

frequency was calibrated, the ultrasound intensity was turned off, and the water balance needle was returned to the vertical line.

Calibration of ultrasound intensity was carried out as per instructions from Rank Stanley Cox. The intensity of the ultrasound was turned up to the intensity to be used in the experimental procedure, 1.5 watts per centimeter squared. The total watts needle indicator was turned to 7.5, which is the total watts to be delivered with an intensity of 1.5 watts per centimeter squared. This value is obtained by multiplying the surface area of the ultrasound head (5.0 $cm^2$) by intensity (1.5 watts per centimeter squared). If the intensity output of the ultrasound unit was accurate, the water balance indicator corresponded exactly with the vertical line. If the intensity output of the ultrasound unit was inaccurate, the water balance indicator came to rest on either side of the vertical line, indicating the intensity output of the ultrasound was either too low or too high. Adjustment of the intensity pot in the back of the ultrasound unit was made until the water balance indicator returned to the vertical line.

Calibration of frequency and intensity was performed on each of the three ultrasound heads, as each of the ultrasound heads delivered a different fixed frequency (0.75 Megahertz, 1.5 Megahertz and 3.0 Megahertz). Calibration of frequencies and intensity was checked by the investigator mid-way through and at the end of the study. No

further calibration adjustments were necessary.

FIGURE 16: Russian Ultraschalleistungmessgerat NMY-3 Ultrasound Calibration Unit and Sonacel Multiphon MK II Ultrasound Unit

# APPENDIX C

## RANDOM TREATMENT SEQUENCE

TABLE 14

Assignment of Randomly Selected Treatment Sequences to Subjects

| Subject Number | Treatment Sequence by Ultrasound Frequency (MHz) | | | |
|---|---|---|---|---|
| 1 | 0.0 | 3.0 | 1.5 | 0.75 |
| 2 | 1.5 | 3.0 | 0.75 | 0.0 |
| 3 | 0.75 | 0.0 | 3.0 | 1.5 |
| 4 | 0.75 | 3.0 | 0.0 | 1.5 |
| 5 | 3.0 | 0.0 | 1.5 | 0.75 |
| 6 | 0.0 | 0.75 | 3.0 | 1.5 |
| 7 | 1.5 | 0.75 | 3.0 | 0.0 |
| 8 | 3.0 | 0.0 | 1.5 | 0.75 |
| 9 | 1.5 | 0.75 | 0.0 | 3.0 |
| 10 | 1.5 | 3.0 | 0.0 | 0.75 |
| 11 | 0.75 | 3.0 | 0.0 | 1.5 |
| 12 | 3.0 | 1.5 | 0.0 | 0.75 |
| 13 | 3.0 | 1.5 | 0.0 | 0.75 |
| 14 | 0.0 | 3.0 | 1.5 | 0.75 |
| 15 | 0.75 | 0.0 | 1.5 | 3.0 |
| 16 | 1.5 | 3.0 | 0.0 | 0.75 |
| 17 | 0.0 | 1.5 | 0.75 | 3.0 |
| 18 | 1.5 | 0.0 | 3.0 | 0.75 |
| 19 | 0.0 | 3.0 | 0.75 | 1.5 |

# APPENDIX D

RAW DATA

**Motor and Sensory Nerve Conduction Velocities**

Motor and sensory nerve conduction velocities were calculated from the raw data obtained from the EMG motor and sensory action potentials recorded on fibre optic recording paper (Figure 17). There were eight action potential tracings recorded per subject per ultrasound treatment: proximal and distal tracings at pre-one minute and immediately pre-treatment, and immediately post and one minute post-treatment. The distance between EMG stimulation sites (in centimeters) and room temperature (in degrees Celcius) were measured and recorded at the end of the treatment session.

Calculation of motor and sensory nerve conduction velocities was performed by the investigator. A horizontal scratch line (using a dissecting needle) was made directly under the isoelectric baseline of the EMG stimulus. Using a two power magnifying glass, a hole was punctured through the fibre-optic recording paper at two points: one at the point of negative deflection of the motor action potential, and one at the peak of the negative deflection of the sensory action potential. Using the two power magnifying glass and a clear plastic T-square, two vertical scratch lines were made on the EMG tracing: one through the hole indicating the initial deflection of the motor action potential, and one through the hole indicating the peak of the sensory action potential. These two scratch lines were made to bisect the inclined dotted timing line found between the motor and

sensory EMG action potential tracings.

Each inclined row of ten dots on the electronic time ruler equals ten milliseconds. The length of time from stimulus artifact to initial deflection of motor action potential and peak of the sensory action potential is the latency time or conduction time, and is calculated by measuring and recording where the vertical scratch lines cross the electronic time ruler. A four-power magnifying glass was used to determine more accurately where the vertical scratch lines crossed the electronic time ruler. By subtracting the time of the distal EMG stimulus from the time of the proximal EMG stimulus, the time required for the nerve impulse to traverse the segment of the nerve between the two stimulation sites is determined. The length of this segment (in millimeters) divided by the difference in latencies (time in milliseconds) gives the conduction velocity of the nerve according to the formula:*

$$\text{Velocity} = \frac{\text{distance}}{\text{time}}$$

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* Smorto MP, Basmajian JV: Clinical Electroneurography: An Introduction to nerve conduction tests, 2nd ed. Williams and Wilkins, Baltimore, 1979

The velocity is expressed in meters per second using the formula:*

$$\frac{\text{millimeters}}{\text{milliseconds}} = \text{meters per second}$$

Motor and sensory conduction velocities are found in Tables 15 and 16.

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* Smorto MP, Basmajian JV: Clinical Electroneurography: An introduction to nerve conduction tests, 2nd ed. Williams and Wilkins, Baltimore, 1979

FIGURE 17: EMG Motor and Sensory Action Potentials on Fibre-Optic Recording Paper

TABLE 15

Motor Nerve Conduction Velocities (in meters per second)
Recorded Pre and Post Ultrasound Treatment

| | ULTRASOUND FREQUENCY IN MEGAHERTZ, AND PRE AND POST-ULTRASOUND TREATMENT EMG RECORDING TIMES | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0.0 | | | | 0.75 | | | | 1.5 | | | | 3.0 | | | |
| n | Pre 1 Minute | Pre 0 Minutes | Post 0 Minutes | Post 1 Minute | Pre 1 Minute | Pre 0 Minutes | Post 0 Minutes | Post 1 Minute | Pre 1 Minute | Pre 0 Minutes | Post 0 Minutes | Post 1 Minute | Pre 1 Minute | Pre 0 Minutes | Post 0 Minutes | Post 1 Minute |
| 1 | 65.60 | 62.28 | 59.28 | 60.74 | 56.76 | 58.33 | 60.00 | 56.00 | 59.43 | 62.09 | 66.03 | 65.00 | 61.54 | 61.54 | 71.64 | 71.64 |
| 2 | 63.10 | 62.22 | 60.54 | 60.54 | 64.66 | 65.56 | 68.41 | 71.52 | 60.53 | 63.89 | 63.01 | 63.89 | 61.33 | 62.16 | 67.65 | 66.67 |
| 3 | 66.67 | 66.67 | 61.97 | 56.41 | 65.07 | 65.07 | 70.32 | 70.32 | 65.23 | 66.25 | 67.30 | 68.39 | 67.54 | 69.83 | 74.91 | 73.57 |
| 4 | 54.55 | 53.93 | 50.00 | 51.61 | 50.24 | 51.50 | 54.21 | 54.93 | 53.49 | 53.49 | 54.12 | 56.10 | 57.88 | 57.21 | 63.90 | 61.50 |
| 5 | 61.33 | 62.16 | 53.49 | 54.76 | 62.42 | 64.38 | 60.30 | 64.38 | 57.30 | 58.89 | 61.45 | 60.57 | 57.90 | 55.00 | 61.11 | 61.97 |
| 6 | 53.66 | 57.14 | 56.41 | 55.70 | 50.60 | 51.85 | 57.89 | 57.53 | 59.73 | 62.29 | 64.12 | 65.07 | 56.11 | 54.59 | 62.15 | 60.30 |
| 7 | 67.74 | 68.85 | 64.62 | 63.64 | 60.27 | 59.47 | 62.78 | 64.57 | 68.89 | 63.01 | 65.71 | 63.89 | 67.46 | 69.54 | 74.10 | 74.10 |
| 8 | 64.79 | 67.65 | 61.33 | 63.89 | 65.16 | 67.33 | 68.47 | 68.47 | 67.10 | 68.20 | 70.51 | 66.03 | 63.84 | 65.71 | 70.77 | 70.77 |
| 9 | 67.33 | 69.66 | 65.16 | 67.33 | 61.82 | 63.75 | 65.81 | 66.89 | 65.57 | 66.67 | 66.67 | 66.67 | 67.74 | 70.00 | 73.68 | 72.41 |
| 10 | 62.05 | 62.86 | 60.50 | 63.68 | 59.00 | 59.00 | 61.30 | 65.56 | 64.79 | 65.71 | 65.71 | 65.71 | 61.58 | 60.00 | 65.92 | 65.92 |
| 11 | 57.07 | 57.84 | 48.09 | 45.05 | 53.49 | 54.76 | 54.76 | 54.18 | 57.44 | 56.00 | 57.44 | 56.71 | 57.14 | 57.89 | 61.11 | 56.41 |
| 12 | 66.23 | 67.33 | 64.13 | 65.16 | 68.65 | 65.97 | 66.84 | 65.13 | 66.11 | 62.63 | 65.21 | 68.00 | 64.32 | 64.32 | 68.00 | 68.00 |
| 13 | 61.46 | 64.62 | 57.93 | 57.93 | 67.78 | 67.78 | 68.73 | 67.78 | 60.25 | 60.25 | 61.82 | 59.50 | 60.53 | 57.50 | 59.74 | 62.16 |
| 14 | 58.97 | 59.74 | 57.50 | 53.49 | 64.44 | 66.29 | 67.25 | 67.25 | 58.33 | 56.76 | 60.87 | 58.33 | 64.79 | 62.16 | 67.65 | 65.71 |
| 15 | 58.70 | 61.92 | 57.22 | 53.18 | 57.84 | 62.03 | 57.07 | 55.58 | 55.38 | 54.00 | 57.60 | 56.84 | 59.13 | 56.67 | 65.81 | 65.81 |
| 16 | 62.77 | 60.90 | 58.29 | 58.29 | 63.75 | 63.75 | 64.76 | 63.75 | 56.76 | 60.87 | 64.62 | 63.64 | 66.67 | 66.67 | 74.07 | 75.47 |
| 17 | 60.00 | 58.46 | 54.29 | 54.94 | 61.82 | 60.90 | 63.75 | 63.75 | 61.11 | 60.27 | 62.86 | 66.67 | 59.73 | 60.54 | 66.87 | 67.88 |
| 18 | 58.97 | 63.01 | 60.53 | 61.33 | 58.00 | 56.59 | 59.49 | 60.26 | 56.67 | 59.50 | 61.82 | 59.50 | 55.81 | 57.83 | 64.00 | 60.76 |
| 19 | 58.18 | 58.18 | 60.54 | 58.95 | 65.40 | 64.38 | 67.54 | 66.45 | 58.92 | 59.73 | 62.29 | 62.29 | 62.50 | 63.49 | 70.18 | 67.80 |

TABLE 16

Sensory Nerve Conduction Velocities (in meters per second)
Recorded Pre and Post Ultrasound Treatment

| | ULTRASOUND FREQUENCY IN MEGAHERTZ, AND PRE AND POST-ULTRASOUND TREATMENT EMG RECORDING TIMES | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0.0 | | | | 0.75 | | | | 1.5 | | | | 3.0 | | | |
| n | Pre 1 Minute | Pre 0 Minutes | Post 0 Minutes | Post 1 Minute | Pre 1 Minute | Pre 0 Minutes | Post 0 Minutes | Post 1 Minute | Pre 1 Minute | Pre 0 Minutes | Post 0 Minutes | Post 1 Minute | Pre 1 Minute | Pre 0 Minutes | Post 0 Minutes | Post 1 Minute |
| 1 | 69.30 | 69.30 | 67.40 | 68.33 | 63.64 | 63.64 | 71.19 | 71.19 | 66.03 | 66.03 | 70.51 | 70.51 | 64.00 | 63.16 | 72.73 | 71.64 |
| 2 | 65.88 | 67.87 | 65.88 | 64.93 | 72.62 | 71.52 | 78.67 | 77.38 | 66.67 | 67.65 | 70.77 | 69.70 | 68.66 | 68.66 | 71.88 | 70.77 |
| 3 | 67.69 | 66.67 | 61.11 | 59.46 | 60.06 | 68.13 | 71.48 | 69.21 | 68.39 | 66.25 | 68.39 | 70.67 | 71.03 | 72.28 | 76.30 | 76.30 |
| 4 | 57.83 | 57.83 | 56.47 | 54.55 | 57.22 | 58.03 | 58.86 | 60.59 | 59.74 | 60.53 | 60.53 | 60.53 | 63.08 | 60.74 | 64.74 | 63.90 |
| 5 | 63.01 | 63.88 | 57.50 | 56.10 | 63.38 | 64.38 | 65.40 | 66.45 | 64.24 | 65.23 | 64.24 | 63.28 | 61.11 | 59.46 | 64.71 | 62.86 |
| 6 | 64.71 | 66.67 | 66.67 | 67.69 | 58.33 | 59.15 | 61.76 | 62.69 | 64.12 | 67.08 | 72.67 | 70.32 | 62.15 | 64.13 | 65.16 | 63.13 |
| 7 | 66.87 | 66.77 | 62.69 | 62.69 | 63.66 | 62.78 | 66.47 | 64.57 | 67.65 | 69.70 | 70.77 | 68.66 | 64.57 | 66.47 | 77.93 | 76.61 |
| 8 | 73.02 | 71.88 | 63.89 | 63.89 | 66.23 | 69.66 | 72.14 | 67.33 | 69.33 | 67.10 | 68.20 | 68.20 | 66.67 | 67.65 | 70.77 | 70.77 |
| 9 | 74.81 | 76.23 | 70.88 | 70.88 | 65.81 | 68.00 | 70.34 | 70.34 | 68.97 | 71.43 | 67.80 | 65.57 | 67.74 | 73.68 | 75.00 | 75.00 |
| 10 | 67.22 | 69.14 | 66.30 | 66.30 | 66.48 | 62.11 | 66.48 | 69.41 | 65.71 | 67.65 | 68.66 | 67.65 | 65.00 | 65.00 | 72.00 | 72.00 |
| 11 | 66.88 | 64.85 | 59.44 | 56.32 | 56.10 | 56.79 | 58.28 | 57.50 | 62.22 | 59.73 | 61.40 | 61.40 | 66.67 | 66.67 | 68.75 | 66.67 |
| 12 | 67.33 | 65.16 | 63.13 | 65.16 | 63.50 | 65.13 | 68.56 | 64.30 | 60.25 | 62.63 | 65.21 | 65.21 | 66.11 | 64.32 | 66.11 | 68.00 |
| 13 | 60.00 | 62.22 | 57.27 | 56.00 | 64.21 | 62.56 | 63.38 | 62.56 | 63.47 | 62.63 | 61.82 | 62.63 | 60.53 | 57.50 | 63.89 | 63.89 |
| 14 | 61.33 | 61.33 | 55.42 | 56.79 | 64.44 | 65.35 | 69.25 | 69.25 | 58.33 | 60.87 | 61.76 | 61.76 | 66.67 | 62.16 | 67.65 | 65.71 |
| 15 | 62.78 | 59.47 | 56.50 | 55.12 | 57.07 | 57.07 | 58.63 | 57.84 | 59.18 | 56.84 | 60.00 | 60.00 | 60.90 | 60.90 | 69.15 | 66.89 |
| 16 | 59.13 | 59.13 | 55.14 | 56.67 | 63.75 | 64.76 | 65.81 | 64.76 | 66.67 | 65.63 | 67.74 | 64.62 | 65.57 | 65.57 | 74.07 | 70.18 |
| 17 | 63.33 | 62.47 | 59.22 | 57.00 | 64.76 | 63.75 | 66.89 | 63.75 | 65.67 | 72.13 | 66.67 | 64.71 | 65.88 | 66.87 | 70.00 | 67.88 |
| 18 | 66.67 | 65.71 | 63.89 | 62.16 | 62.70 | 62.70 | 64.44 | 63.56 | 65.21 | 62.63 | 63.47 | 64.32 | 64.86 | 63.16 | 67.61 | 65.75 |
| 19 | 59.73 | 63.10 | 60.54 | 59.73 | 64.38 | 65.40 | 66.45 | 67.54 | 62.29 | 64.12 | 66.06 | 66.06 | 68.97 | 70.18 | 78.43 | 74.07 |